

PETROGRAPHY AND DIAGENESIS OF THE HIGH-LYING FERRICRETES OF EL BAHARIYA DEPRESSION, WESTERN DESERT, EGYPT

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ملخص

يتضمن هذا البحث دراسات بتروجرافية على القشرة السطحية اللاتيريتية (فركريت) التي تنتشر في منخفض الواحات البحرية بالصحراء الغربية والتي تمثل نتائج عمليات تجوئه (لاتيريتيه) قديمة أثرت على صخور المنطقة. وتغطي هذه القشرة بقايا الإرتفاعات وهضاب مخروطية الشكل. وأمكن تقسيم هذه الرواسب اللاتيريتيه إلى ثلاث نطاقات تعرية مميزة. الكيميائية وتغيرات ما بعد الترسيب والتي صاحبت عمليات التعرية وتكوين هذا النوع من التربه اللاتيريتيه.

ABSTRACT

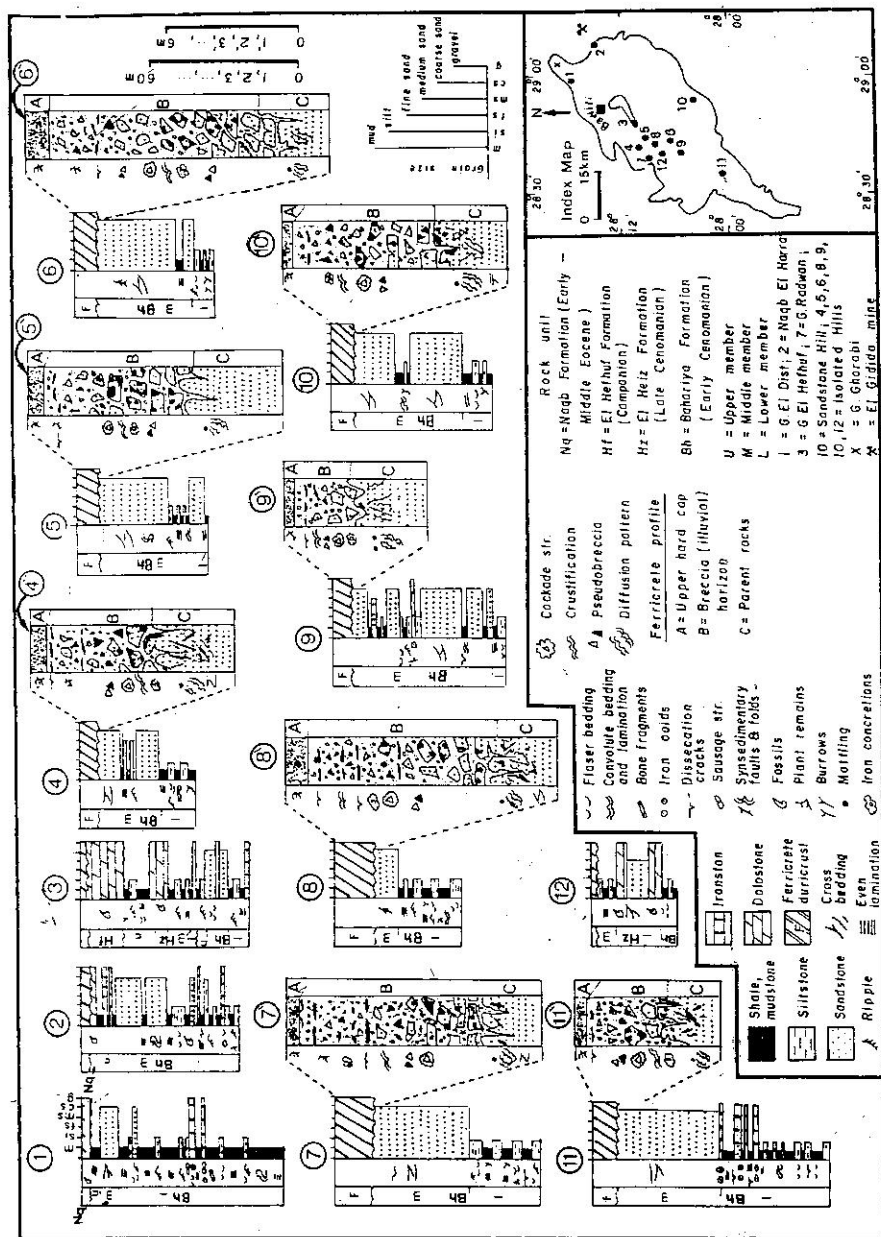
In El Bahariya depression, surficial ferricrete covers the bevelled summits of residual landforms and the surrounding scarps and delineates the level of an old erosion surface. The ferricrete profile comprises three horizons:

- 1) an upper indurated horizon (hard cap) rich in oxidized plant remains, biogenic pyrite framboids and crustified goethite;
- 2) illuvial (breccia) horizon consisting of altered breccia fragments embedded in a matrix of iron sesquioxides and kaolinitic clays, and
- 3) weathered parent rocks, either Cretaceous clastics or karstified Eocene dolostones. The microscopic characters of the parent rocks and their textural evolution during the pedogenesis and the mineral composition and textures of the different ferricrete horizons are described in detail. The behaviour of the including heavy minerals during the course of weathering is also considered and discussed. The different geological, mineralogical, physico-chemical and biogenic processes involved during ferricrete formation are deduced.

INTRODUCTION

Remnants of a high - level ferricrete duricrust are widely distributed in El Bahariya depression, Western Desert, Egypt (Fig. 1). This ferricrete type occurs in genetic association with deeply weathered clastic and carbonate rocks and represents a formerly extensive land surface (old erosion surface) on which deep weathering processes took place (El Aref et al., 1991). Genetically related lateritic deposits are the surficial iron crust of G. Ghorabi and the iron ores of El Gedida locality (El Aref and Lotfy, 1989 and El Aref et al., 1991). Low-lying ferricretes are also recorded in El Bahariya depression, either as bench-like form or thin crust capping the pediments of the depression. They are regarded to be the result of subsequent etch planation and pedimentation processes that acted upon the old erosion surface and related ferricrete profile and resulted in continuous sideways recession of the slopes, ultimately into the formation of dissected lateritized plains and duricrusted tablelands, ridges and cone-hills (El Aref et al., 1991). The high-lying ferricrete was described in the previous literatures as El Heiz low grade iron ore or 'Radwan Formation' (27 to 30.29% iron content) of either lacustrine or hydrothermal replacement origin (Ball and Beadnell, 1903; Hume, 1909; Zaatout, 1958; El Akaad and Issawi, 1963; Said and Issawi, 1964; Amer, 1968; Basta and Amer, 1969a, b, c, d; Amer, 1973; Tosson and Saad, 1974; Dardir, 1975; Awadallah et al., 1984a, b and Shallan et al., 1984, 1986). Mücke and Agthe (1988) described the ferruginous rocks of El Bahariya depression including the ferricrete units as continental red beds formed by epigenetic mineralization of the Bahariya Formation during the Cretaceous-Tertiary transition.

The present work provides an attempt to clarify the paragenesis and fabric evolutions of the different horizons of the high-lying ferricrete profile and the diagenetic processes and environmental conditions prevailed during the pedogenesis. The behaviour of the including heavy minerals during the course of weathering is also considered. Representative 12 stratigraphic sections were measured from different localities in El Bahariya depression in order to elucidate the composition and distribution of the exposed rock units and their relation with the overlying ferricrete caps. The ferricrete profile of each section, provided by natural outcrops, was also measured and studied (Fig. 1). Representative samples were systematically collected from the parent rocks and the different ferricrete horizons and petrographically investigated using thin and polished sections. The identification of the oxide and clay minerals was confirmed by X-ray diffraction (XRD). Heavy minerals were separated from the different horizons of four ferricrete profiles using bromoform (Sp. Gr. 2.85) and magnetic separation. The nomenclature of the original stratigraphic units of El Bahariya depression is adopted from the stratigraphic scheme of El Akaad and Issawi (1963) and Said and Issawi (1964).



The Bahariya Formation is further subdivided into three conspicuous members based on the predominant lithology and sedimentary structures of each member (Fig. 1). The discrimination of the ferricrete fabrics depends upon the conventional nomenclature and terminology for siliceous and ferruginous sediments and laterites, with emphasis on matrix - skeletal grain relationships (Brewer, 1964; Pettijohn, 1975; Tucker, 1981; Bardossy, 1982; Summerfield, 1983; Laznicka, 1988 and Roquin et al., 1990, among others).

Morphostratigraphic setting of the high-lying ferricretes

The high-lying ferricrete profile forms a characteristic morphologic marker (~ 270 to 320 m, a. s. l.) capping the bevelled summits of the following rock units:

- 1) the middle sandstone member of the Bahariya Formation (Early Cenomanian). This ferricrete cap is well represented in G. Radwan and Sandstone Hill forming a partially dissected lateritized plains and in the central part of the depression forming the upper cliff segment of the slope profiles of isolated conehills, elongated ridges and tablelands;
- 2) the middle sandstone member of El Heiz Formation (Late Cenomanian),
- 3) the karstified dolostones of the Naqb Formation (Early Middle Eocene), especially along the northern scarp of the depression. The individual ferricrete unit occurs as a horizontal and dark coloured strata, 6 to 17m thick, showing gradational contact with the underlying intact rocks. It is subdivided into three peculiar horizons which correspond to the well known A, B and C horizons of the typical laterite profiles. The tops of the exposed clastic rocks of El Hefhuf Formation (Campanian) are also covered by dark brown to black indurated cap, up to 6m thick, consisting of highly ferruginated sandstone breccia fragments and iron pisolites and concretions embedded in red ocherous materials.

High-lying ferricrete overlying the Bahariya Formation

C and B horizons

The lower C horizon of this profile includes fresh to slightly weathered rocks which occur directly beneath the breccia horizon and are still exhibiting the original bedding nature and other sedimentary structures of the middle member of the Bahariya Formation. They consist mainly of white to yellow coarse-grained to pebbly sandstone (Fig. 1; Type 1, Fig. 2). Upwardly, the intact rocks grade into highly fractured, brecciated, mottled, silicified and ferruginated rocks, their white and yellow colours grade into deep brown and black (Pl. I a, b). Concentric iron rich layers or "liesegang rings", resulted from diffusion processes, are commonly

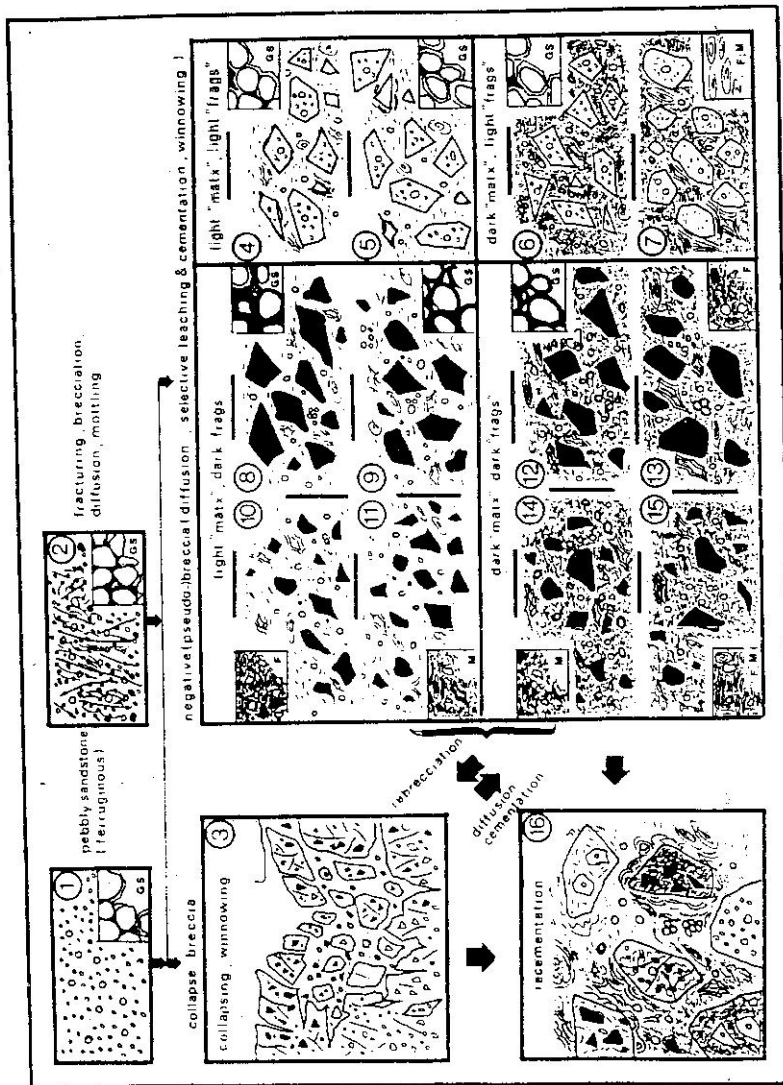


Fig. 2. Megascopic and microscopic characters of the C and B horizons of the ferricrete profile. The microscopic fabrics of the "breccia fragments" are shown in the small squares
GS = grain - supported fabric; F = floating fabric; M = matrix fabric.

PLATE 1

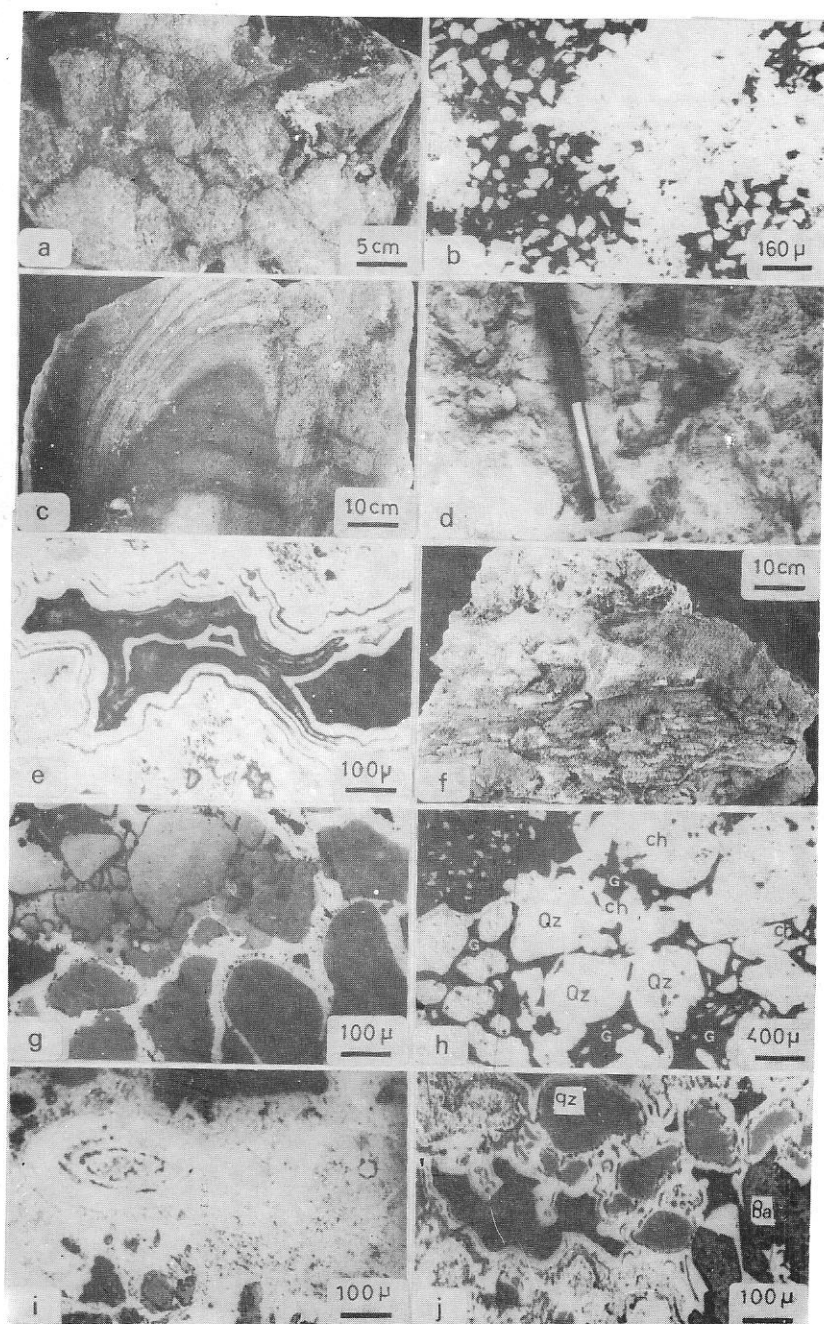


PLATE I

- a) Highly fractured and brecciated sandstone, C horizon.
- b) Mottled sandstone of the C horizon, (T.S., O.L.).
- c) Concentric layers of iron sesquioxides or "Liesegang rings", C horizon.
- d) Sandstone fragments in iron rich matrix of the B horizon.
- e) Crustified layers of colloform goethite, the residual vugs (black) are filled with ferruginous clays, (P.S.).
- f) Ferruginated and silicified plant root, B horizon.
- g) Goethite films and coatings (white) around ferruginated clast (upper left corner) as well as discrete quartz grains (grey), B horizon.
- h) Alternating layers of goethite (G) and chalcedony (Ch) around ferruginated clasts and quartz grains (qz), B horizon, (T.S., O.L.).
- i) Goethite pisolites embedded in a matrix of goethite dust and kaolinitic clays, (P. S.).
- j) Rhythmic alternation fragments, earthy products, barite crystals (Ba) or residuum quartz grains (qz).

T.S. = *Thin Section.*

P. S. = *Polished Section.*

O.L. = *Ordinary Light.*

C.N. = *Crossed Nicols.*

developed around the capillary spaces (fractures and bedding planes), (Pl. Ic). Intensive degree of diffusion and concentration of iron sesquioxides form highly ferruginated sandstone varieties around the capillary spaces (Type 2, Fig. 2). An advanced stage of fracturing and fragmentation led to gradual detachment of angular to subangular sandstone blocks, cobbles and boulders in a matrix of ocherous materials.

The breccia (B) horizon, 2 to 9m thick, consists of altered sandstone fragments of variable shapes, sizes, composition and proportion set in iron-rich matrix (Type 3, Fig. 2; Pl. Id). The fragment / matrix ratio decreases gradually towards the upper (A) horizon.

The matrix between the breccia fragments varies in colour from yellowish white to dark brown and black and is made up of the following constituents:

- 1) irregular layers or patches of discrete, well rounded and pebble-sized quartz grains cemented by goethite;

- 2) lense shaped bodies of yellow kaolinitic clays mixed with sandy to silty yellow and red ochers, pisolitic in part,

- 3) irregular layers and lenses of iron pisolites, spheroids and concretions grading into convolute and twisted crustified fabric (Pl. Ie). Iron encrustations around breccia fragments forming cockade structure,

- 4) dissected thin layers of red organic rich mudstone showing desiccation cracks, horizontally arranged mudstone clasts are also present, and

- 5) highly ferruginated wood debris and molds (Pl. If). Load structure, formed by gravitational settling of breccia fragments, plant debris, residuum quartz grains or iron concretions into the underlying clayey ocherous deposits is common. Microscopically, the binding materials of the matrix are represented mainly by goethite, hematite, kaolinite, chalcedony and quartz. Pyrite, barite, pyrolusite and psilomelane occur in subordinate amount. These minerals exhibit the following microscopic textures :

- 1) films and coatings of goethite on ferruginated clasts and or discrete pebble-sized quartz grains (Pl. Ig). Towards the upper part of the breccia horizon, the clasts and quartz grains are cemented by alternating layers of goethite and chalcedony (Pl. Ih),

- 2) iron pisolites and glaeboles, 0.5 to 2 mm in diameter, in a matrix of goethite dust and kaolinitic clay (Pl. Ii). They show signs of pre-consolidation deformation as they often distorted, twisted and squeezed. Some of which are also dissected by microfractures filled with clays.

3) concentric concretions of alternating layers of goethite, hematite, pyrolusite and kaolinite. They occur either as isolated particles, up to 10 cm in diameter, or as coalesced masses of a mammillary surface. Remnants of the host matrix and skeletal quartz grains are trapped between the coalesced concretions,

4) crustified texture, quite frequently a rhythmic alternation can be seen between colloform goethite, and hematite and red earth with individual laminae of up to 50 μ thick (Pl. Ij) ,

5) concentric spheroids of colloform hematite growing directly on the internal walls of residual cavities and vugs left behind the crustified layers or laminae (Pl. IIa), and

6) authigenic pyrite and barite crystals growing within the earthy materials. Pyrite shows isolated minute crystals or framboids, 3 to 70 μ in diameter. The framboids may occur in groups forming super - framboids or rogen pyrite (Ncube et al., 1978 and Papadakis and Amstutz, 1980). Barite crystals grow frequently within the earthy matrix and exhibit idiomorphic terminations against subsequent colloform goethite layers or laminae.

The breccia fragments of the B horizon are of boulder, cobble and pebble sizes, angular to subangular, however, they may be locally subrounded to rounded (Type 3, Fig. 2). They are highly silicified and ferruginated, the effect of which increases gradually from their outer margins to their central parts and is favoured around intersected joints and cracks. The outcome of the selective silicification and ferruginization is the production of pseudobreccia (negative breccia) fabrics, consisting of patchy and irregular shaped masses or "clasts" of light colour surrounded by darker "matrix" or vice-versa (Types 4 to 15, Fig. 2; Pl. IIb, c). Rebrecciation , reworking and recementation of the breccia fragments are commonly observed (Type 16, Fig. 2). The different microscopic fabrics and their evolutionary trends observed in the intact sandstone and the altered breccia fragments are illustrated and summarized in figure 3.

The intact white to yellow sandstone portions are mainly quartz arenite consisting of quartz grains (> 95%) with subordinate amount of feldspars and chert fragments. Zircon, tourmaline, staurolite, kyanite, magnetite, garnet, rutile and ilmenite are the common accessories. The skeletal grains are of medium to coarse sand size, subrounded to rounded and moderately sorted. The majority of which are supporting each other by contacts of tangential point type (Type I, Fig. 3). Some grains are partially coated by quartz overgrowths.

The silicified breccia fragments are predominant in the lower-most part of the B horizon forming a characteristic silicified zone. They show grain-supported (GS) fabric; with optically continuous quartz overgrowths giving rise to interlocked sutured grain boundaries (Type IIa, Fig. 3; Pl. IIId).

PLATE II

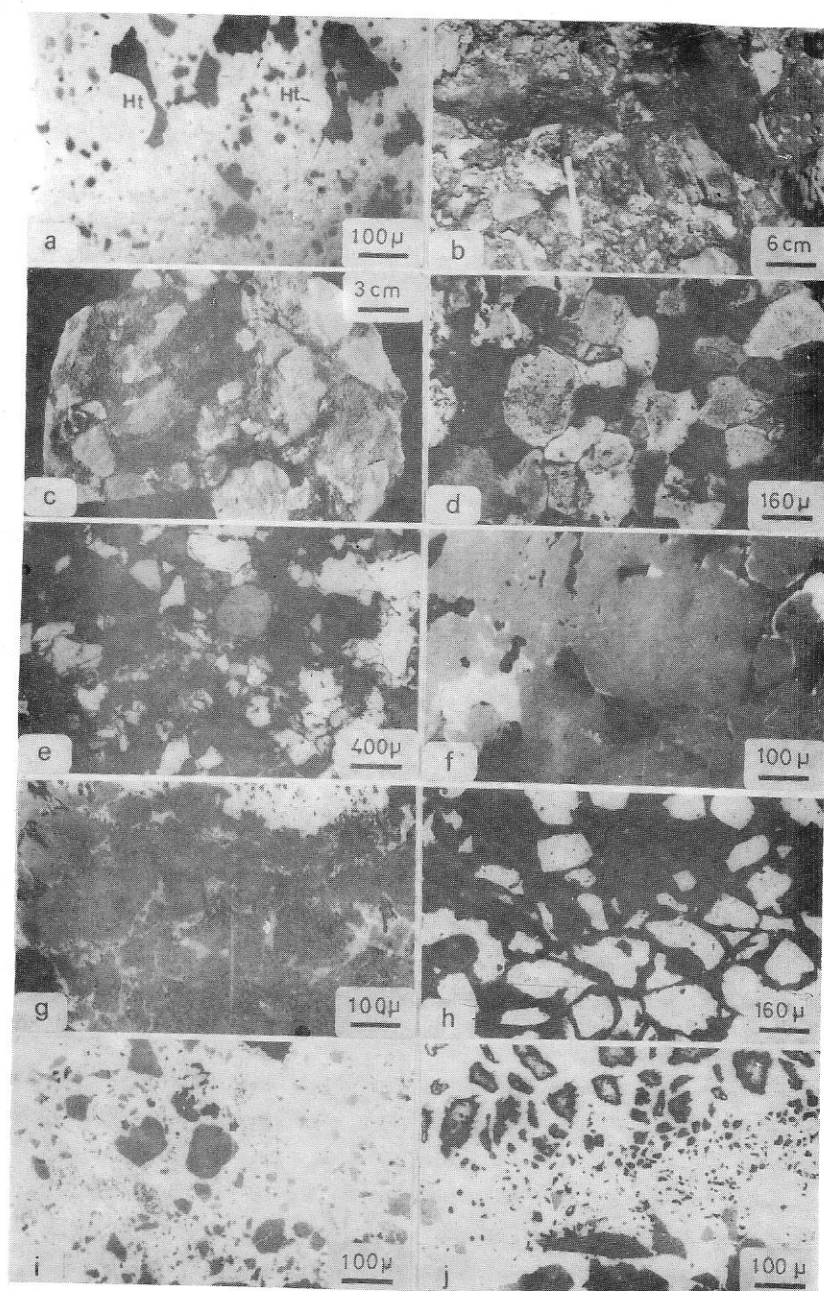


PLATE II

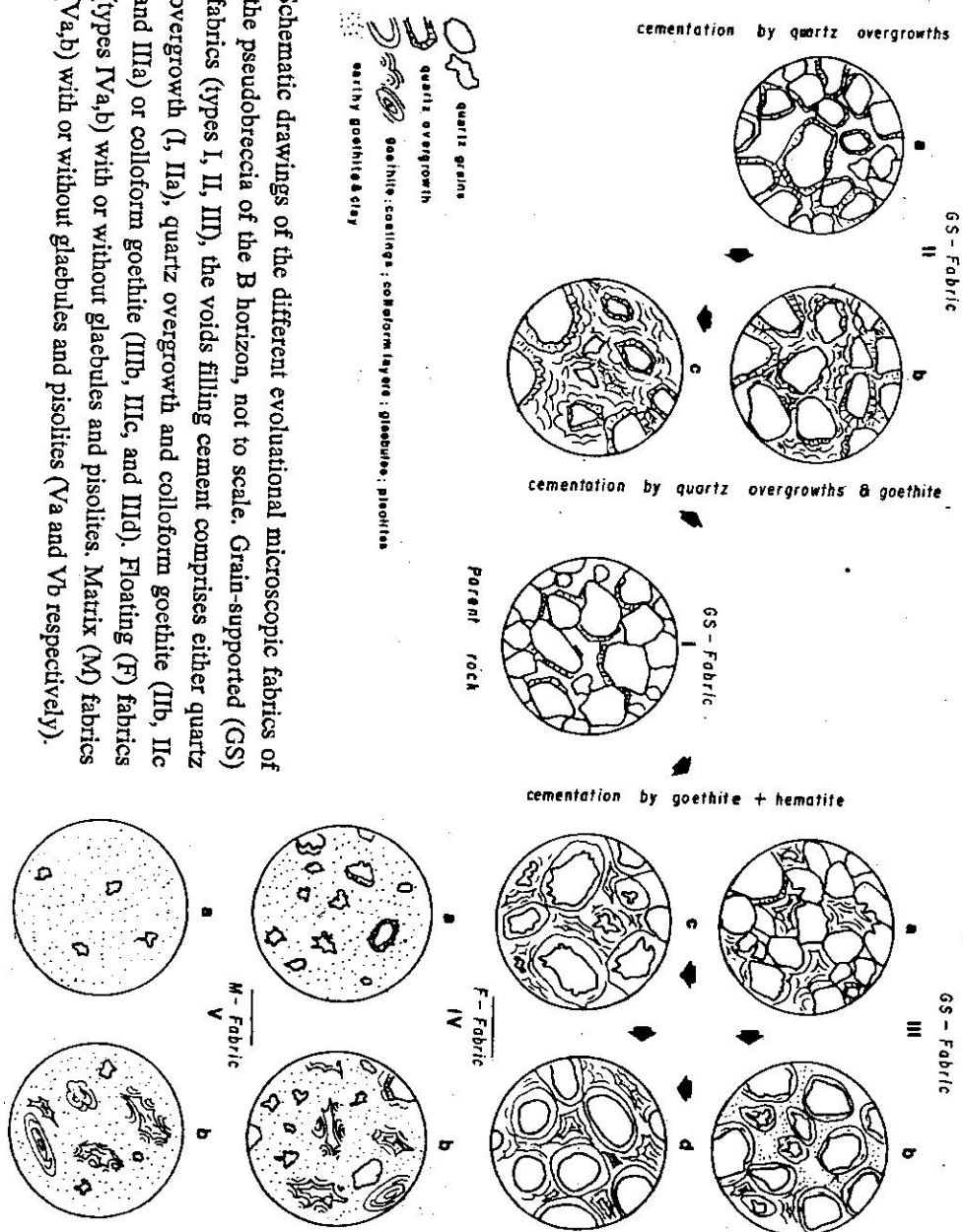
- a) Concentric spheroids of colloform hematite (Ht) growing on the residual vugs and cavities, matrix of the B horizon, (P. S.).
- b & c) Pseudobreccia (negative breccia) fabric consisting of light colour "clasts" surrounded by darker "matrix", B horizon,
- d) Grain-supported (GS) fabric in the silicified breccia fragments of the B horizon, (T.S., C.N.).
- e & f) Thin and polished photomicrographs of silicified-ferruginated breccia fragment, skeletal quartz grains are partially coated by quartz overgrowths and goethite (arrows).
- g) Progressive corrosion of the quartz overgrowths and skeletal quartz grains by goethite films (white), (P.S.).
- h) Completely coated quartz grains (lower part of the photo) in the silicified ferruginated fragments, white: quartz grains; black : goethite, (T.S., O.L.)
- i) Highly corroded quartz grains (grey) floating in massive earthy goethite, (P.S.).
- j) Matrix (M) fabric consisting of completely corroded quartz grains (grey) embedded in earthy goethite matrix (white), (P.S.).

T.S. = *Thin Section*, *P.S.* = *Polished Section*,

O.L. = *Ordinary Light*. *C.N.* = *Crossed Nicols*.

Fig. 3.

Schematic drawings of the different evolutionary microscopic fabrics of the pseudobreccia of the B horizon, not to scale. Grain-supported (GS) fabrics (types I, II, III), the voids filling cement comprises either quartz overgrowth (I, IIa), quartz overgrowth and colloform goethite (IIb, IIc and IIIa) or colloform goethite (IIIb, IIId, and IIId). Floating (F) fabrics (types IVa,b) with or without glaebules and pisolites. Matrix (M) fabrics (Va,b) with or without glaebules and pisolites (Va and Vb respectively).



In the silicified - ferruginated fragments two main fabrics are recognized, grain-supported (GS) fabric and floating (F) fabric. The GS fabric consists of quartz grains forming self-supporting framework with optically continuous quartz overgrowths and goethite films (Pl. IIe, f). The overgrowth faces are highly corroded, embayed and partially coated by goethite (Type IIb, Fig. 3). Progressive corrosion of the quartz overgrowths as well as the original quartz grains is shown by an irregular or embayed contacts between the goethite cement and grains (Pl. IIg). This is carried so far that, the original grains are represented by a few small residuals of irregular outlines, completely coated by colloform goethite (Type IIc, Fig. 3; Pl. II h). The remaining voids between the colloform goethite layers are either empty or filled with earthy goethite mixed with kaolinite. Ultimate dislocation and corrosion of the overgrowth surfaces and original skeletal grains together with continuous accumulation of earthy goethite and clay form a floating (F) fabric (Types IVa, b; Fig. 3), where the skeletal grains varies widely down to arbitrary lower limit of 5% (Pl. Iii). The matrix between the residual grains consists of earthy goethite and kaolinite (Type IVa, Fig. 3) and may include small glaebules, goede-like forms of concentric colloform goethite and goethite pisolites (Type IVb, Fig3). The colloform goethite grows directly on the earthy matrix and forms simple type of crustification which may grade into successive alternating laminae. Rod-like crystals of hematite occur on the younger colloform goethite crusts and show idiomorphic outlines towards the residual vugs. Irregular areas of matrix (M) fabric (< 5% skeletal grains, types Va, b, Fig. 3) are widely distributed within some silicified ferruginated fragments (Pl. IIj).

The wholly ferruginated sandstone fragments consists of irregular areas of either grain-supported, floating or matrix fabrics. In the grain-supported (GS) fabric (Type IIIa, Fig. 3), the interstitial spaces are filled with colloform goethite crusts, up to 100 μ thick (Pl. IIIa). The thickness of these crusts decreases towards the tangential point contacts (Pl. IIIb). Complete coatings on discrete small skeletal grains are common. The outer surfaces of these coatings form a sharp limit towards the remaining vugs which are often filled with orthosparite or earthy products. Type IIIb (Fig. 3) shows partial corrosion and embayment of the outer surfaces of the large quartz grains as well as intensive etching of the smaller ones. The skeletal grains appear to be pushed away from each other, where coating by colloform goethite tend to gradually round out the corroded grains (Pl. IIIb). The colloform goethite is often present as investing concentric layers around the etched surfaces. Such coatings include dusty materials, especially along the boundaries with the skeletal grains and their outer zones may consist of spear-headed hematite and / or goethite crystals. Types IIIc and IIib (Fig. 3) represent progressive stages of dislocation of the large quartz grains and ultimate

PLATE III

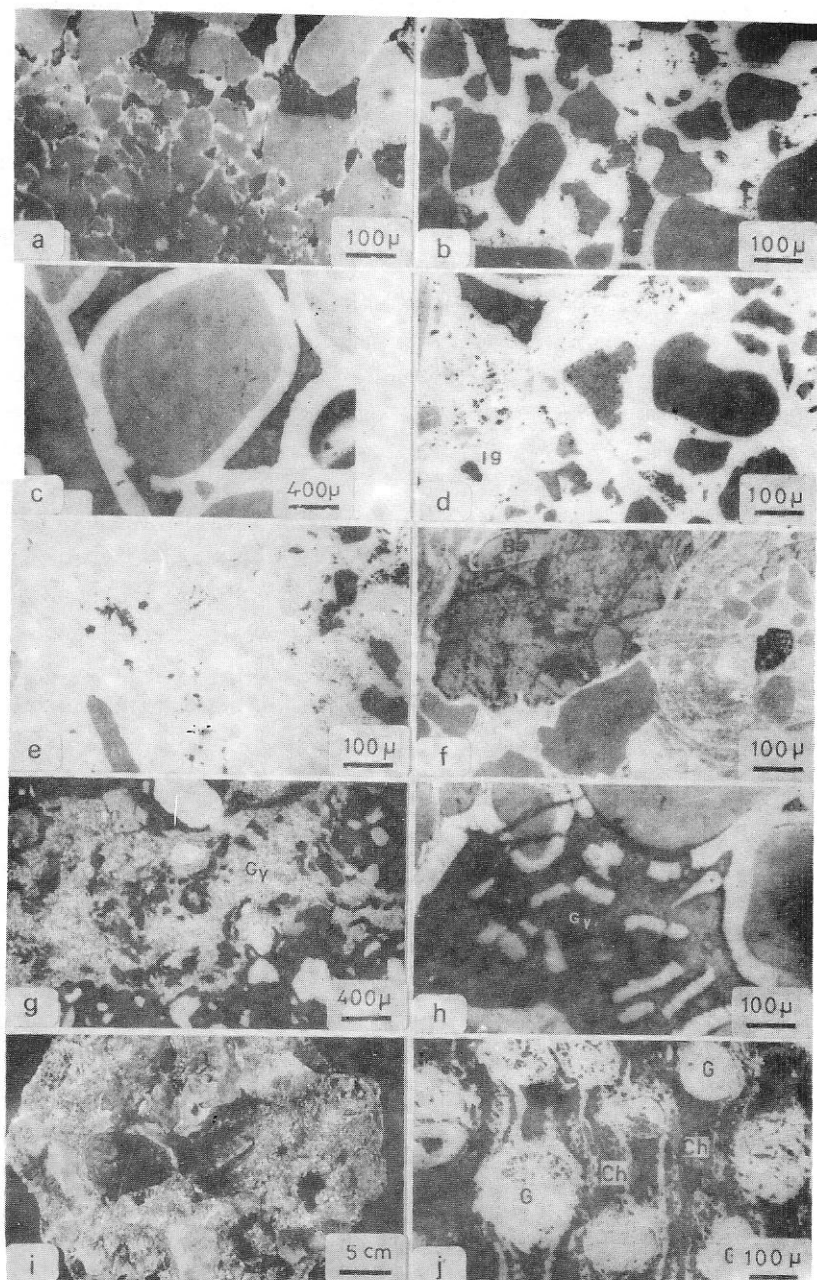


PLATE III

- a) Grain-supported (GS) fabric of the ferruginated fragments of the B horizon, (P.S).
- b) corroded quartz grains (grey) completely coated by colloform goethite (white), the thickness of the goethite layers decreases towards the tangential point contact, (P.S.).
- c) Well rounded quartz grains (grey) completely coated by colloform goethite layers (white), (P.S.).
- d) Floating (F) fabric with iron glaeboles (ig), (P.S.).
- e) Matrix fabric consisting of very small embayed quartz grains (dark grey) floating in earthy goethite matrix (white), the residual vugs (arrows) are lined with spear-headed hematite (arrows), (P.S.).
- f) Barite bearing sandstone fragment, iron and clay pisolite (right part of the photo) and residual quartz grains (grey) cemented by colloform goethite (white), upper part of the sandy A horizon, (P.S.).
- g) and h) Thin and polished photomicrographs showing the detached goethite crusts (black in figure g and white in figure h) and their cementation by gypsum (Gy).
- i) Root molds (black grooves) in the A horizon.
- j) Polished section of cellular plant structure, G = goethite, ch = chalcedony; black = clay.

T.S. = *Thin Section.*

P.S. = *Polished Section.*

O.L. = *Ordinary Light.*

C.N. = *Crossed Nicols.*

corrosion of their edges and the small grains. The intact skeletal grains, up to 1.5 mm in diameter, are well rounded, and completely surrounded by a film of massive or colloform goethite (P1. IIIc). The associated floating (F) fabric (Types IVa, b; Fig. 3) consists of highly corroded and embayed skeletal grains with or without remnants of quartz overgrowths and goethite films, embedded in massive matrix of clay and iron sesquioxides. Goethite glaeboles, pisolites and small scale concretions are randomly distributed within the matrix (P1. IIIId). The glaeboles (mostly of undifferentiated internal fabric) are prolate to equant in shape, ranging in size from 200 μ to 5 mm, recognizable by their greater concentration of massive goethite and their distinct boundaries with the enclosing soil material. Some of which are internally homogeneous inside and consist mainly of cryptocrystalline goethite, others are inhomogeneous consisting of silty quartz grains embedded in earthy goethite resembling the fabric of the adjacent matrix. The glaeboles are often encrusted by concentric crustified layers of colloform goethite. Crustified goethite layers also grow within the matrix, along vugs, plant molds or intersectional fractures. An advanced stage of accumulation of earthy products and final corrosion of the remaining skeletal grain component give rise to areas of massive (M) fabric (Types Va, b; Fig. 3; P1. IIIe). This fabric is composed entirely of materials similar to the matrix of the above described floating (F) fabric, but with skeletal grain component > 5%.

Sandy (A) horizon (hard cap)

The uppermost horizon of the ferricrete profile is represented by a hard, massive and black layer, 30 to 100 cm thick, generally more resistant to weathering than the underlying rocks and stands out as a prominent feature forming a characteristic hard horizon. The constituents of this horizon pass gradually into the softer sediments of the underlying B horizon. They include rounded to well rounded skeletal quartz grains, lithoclasts of quartzite, and barite bearing sandstones and abundant plant remains as root molds, algal filaments, plant tissues and cellular structures. These are cemented by colloform goethite, silica, oxidized pyrite framboids, barite, gypsum, anhydrite and less abundant calcite. These materials show evidences of fracturing, brecciation and recementation. The uppermost part of this horizon is formed essentially of crustified goethite together with abundant plant remains. Goethite with or without clay and silica exhibit the following morphologic features :

- 1) thin films or coatings surrounding breccia fragments, discrete rounded quartz grains and barite crystals of rosette form (P1. IIIf). Such coatings may grade into concentric crustified layers or coalesced concretions. They are commonly fractured and gradually shifted from the encrusted fragments or grains,

the resulted particles are usually cemented by calcite, gypsum and anhydrite (P1. IIIg, h). This feature indicates diagenetic dissection of the goethite coatings and crusts during the deposition of the evaporitic minerals in dry periods;

2) mesoscopic pisolites, up to 2.5 mm in diameter, consisting of thin layers of earthy goethite and clay with nuclei of corroded quartz grains, massive earthy products and / or debris of barite crystals;

3) preservation of cellular structures and tissues of plant remains (P1. IIIi). Massive goethite shows a confined relation with certain positions in the preserved plant structures (P1. IIIj). These include : intracellular goethite deposited within the cell interiors; massive goethite filling the intercellular spaces; thin goethite crusts replacing cell walls; and radial goethite crystals and clays replacing elongated tissues. Most of the replaced cells and tissues are lined by successive layers of chalcedonic overlays and / or equigranular quartz mosaic (P1. IVa), and

4) goethite pseudomorphs after pyrite framboids, minute pyrite crystals and clusters, which are commonly distributed within the intracellular and intercellular spaces. Barite shows prismatic crystals of rosette or flower-like pattern growing on and encrusted by crustified goethite layers or stalactiform crystals growing within the empty spaces left behind the goethite bands and laminae (P1. IVb - d). Calcite is found as blocky crystals cementing coated quartz grains and barite crystals or horizontally arranged nodules of calcrete type, up to 5 cm in diameter, especially along the contact with the breccia horizon.

Heavy residue

Four representative ferricrete profiles have been chosen for heavy mineral separation (sections 4', 8', 9' and 11', Fig. 1). The variation of the heavy mineral content as well as ilmenite and magnetite content among the different ferricrete horizons are given in Table 1 and graphically illustrated in Figures 4 and 5. Microscopic observations along with the results of the concentration processes reveal the following :

1. The heavy mineral concentrates separated from the samples of the C horizon consist mainly of iron oxides, ilmenite, magnetite, zircon, tourmaline, rutile, garnet, kyanite and staurolite.
2. There is a close similarity between the heavy mineral suits in the ferricrete duricrust and those of the immediately underlying parent rocks.
3. The hard cap is generally enriched in more resistant minerals (zircon and tourmaline) and depleted in the unstable heavy minerals (ilmenite and magnetite), when compared with the underlying breccia (B) horizon and the parent rocks (Fig. 4).

PLATE IV

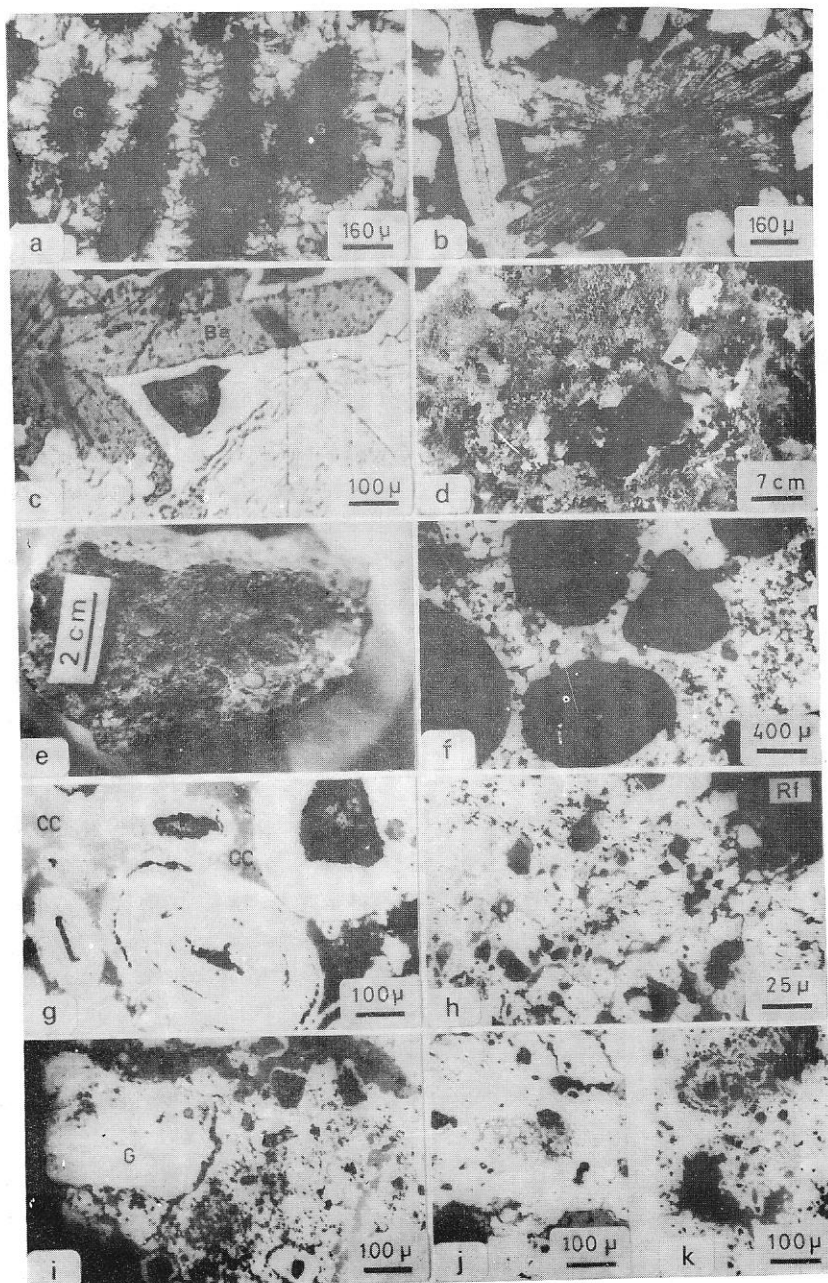


PLATE IV

- a) Cell walls and tissues preserved by successive layers of chalcedonic overlying (white) and goethite (G), A horizon, (T.S., C.N.).
- b) Flower-like pattern of barite crystals cemented by colloform goethite (black), A horizon, (T.S., O.L.).
- c) Idiomorphic barite crystals (Ba) encrusted by concentric colloform layers of goethite, (P.S.)
- d) Stalactiform barite (arrow) growing within residual cavity A horizon.
- e) Iron pisolites of the middle horizon of the ferricrete profile over-lying El Heiz Formation.
- f) Quartz mosaic cementing iron pisolites (black), (T.S.).
- g) Goethite pisolites cemented by blocky calcite (CC), (P.S.).
- h) Rottenstone fragments (Rf) and embayed quartz grains (grey) embedded in a ferruginous matrix of the ferricrete profile overlying the Naqb Formation, (P.S.).
- i) Iron glaeubules (G) and small pyrite framboids (arrows) within ferruginous matrix. (P.S.).
- j) Mouldic cavity (central part of the photo) filled with oxidized pyrite framboids (arrow) and surrounded by massive goethite (white), (P.S.).
- k) Oxidized spindle-shaped siderite crystals (arrow) and calcite (grey) within small vugs in massive goethite matrix (white), (P.S.).

T.S. = *Thin Section.* *P.S.* = *Polished Section.*
O.L. = *Ordinary Light.* *C.N.* = *Crossed Nicols.*

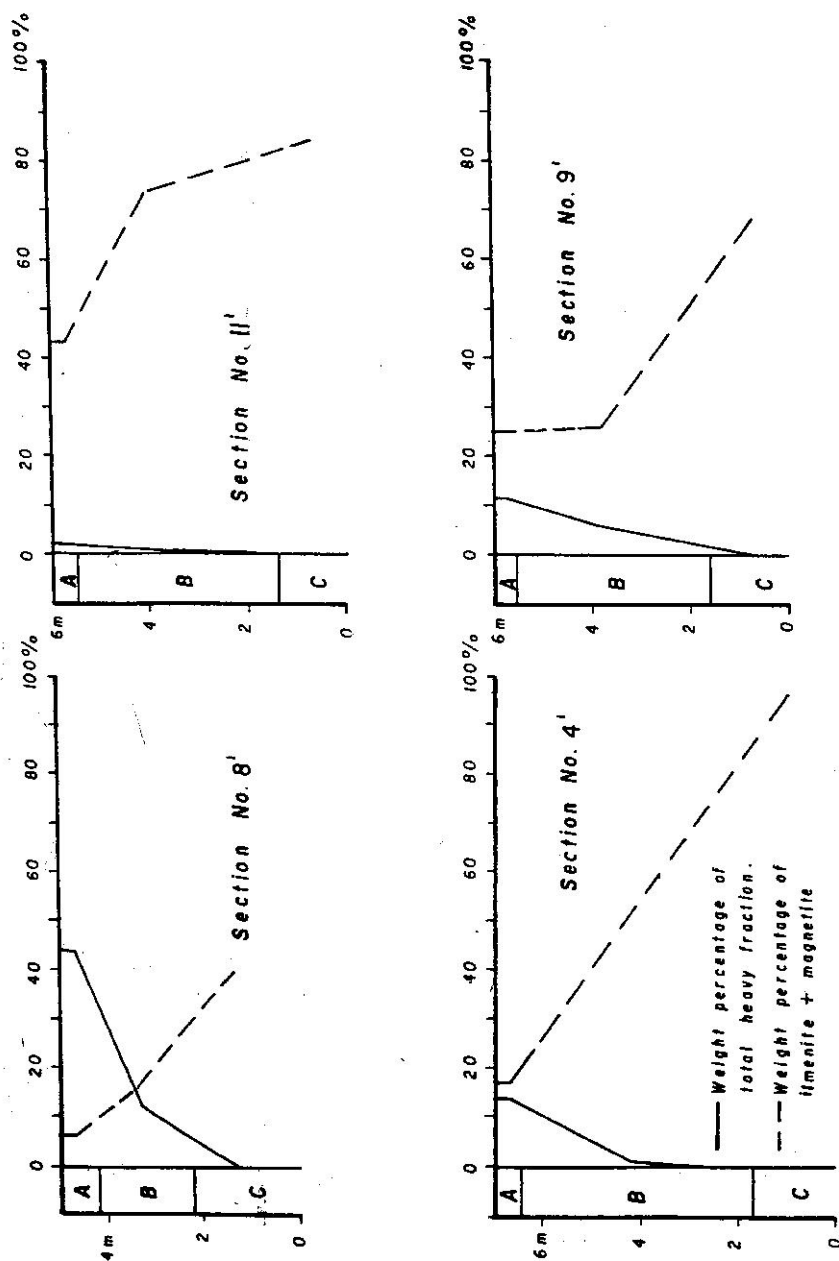


Fig. 4. Variation of heavy fraction and ilmenite + magnetite in the analysed ferricrete profiles.

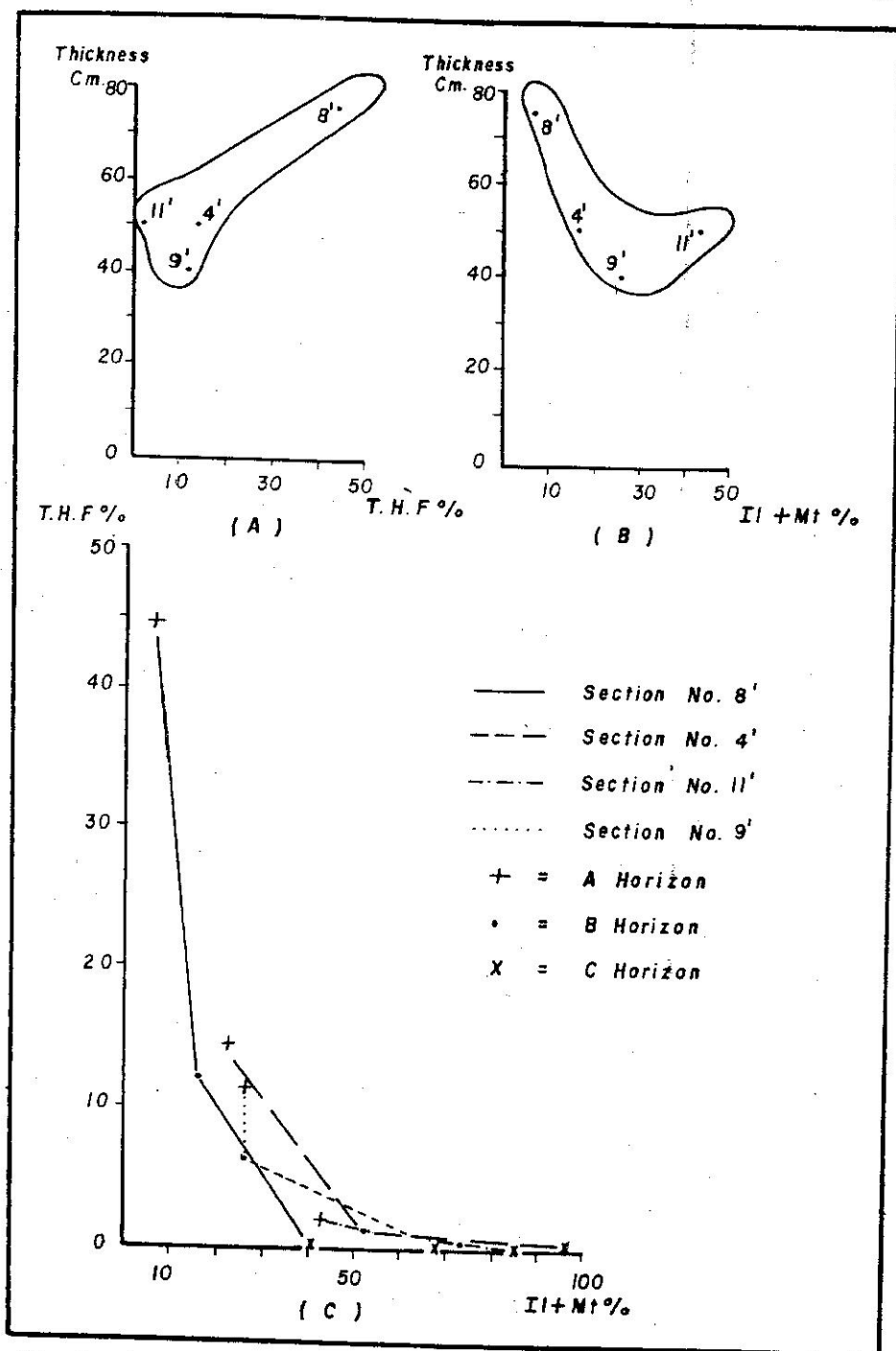


Fig. 5. Plot diagrams of the results of the heavy mineral separation.

Table 1 . The results of heavy mineral concentration processes.

1	2	3	4
8'	A	44.12	6.77
	B	12.29	16.48
	C	0.16	39.09
4'	A	14.21	17.34
	B	1.34	52.13
	C	0.23	96.17
11	A	2.22	43.23
	B	0.02	74.28
	C	0.002	84.84
9'	A	11.53	25.58
	B	6.22	26.75
	C	0.47	67.52

1 = Analysed profiles (Fig. 1),

2 = Ferricrete horizons,

3 = $\frac{\text{Total heavy fraction (T.H.F.)}}{\text{Total sample}}$ wt%,

4 = $\frac{\text{Ilmenite + magnetite (Il . + Mt)}}{\text{Total heavy fraction (T. H. F.)}}$ wt%,

4. Generally, the total percentages of the heavy mineral fraction in the uppermost A horizon are higher than those of the underlying B and C horizons. The A horizon of section 8' contains the highest value, where it attains the higher thickness and iron content (Fig. 5A).
5. The total heavy mineral fraction increases with the thickness of the A horizon whereas the ilmenite and magnetite percentage decreases (Fig. 5 B).
6. The decrease in ilmenite and magnetite is accompanied by an increase in the weight percentage of the total heavy fraction, both within the A horizons and among the other horizons of the analysed profiles (Fig. 5C).

These results match well with the field, megascopic and microscopic observations which indicate in situ formation of this ferricrete duricrust through deep weathering processes. These processes led to the oxidation of the unstable minerals (magnetite and ilmenite) in the oxidation zone and concentration of the more stable minerals (zircon and tourmaline) in the upper A horizon.

Ferricrete overlying El Heiz Formation

This ferricrete type (Fig. 6) covers the exposed sandstones of the middle member of El Heiz Formation. It attains up to 17 m thick and consists of three gradational horizons. The lower horizon consists of highly silicified and fractured sandstones, becoming darker in colour, mottled, highly fractured and brecciated towards the overlying horizon. The silicified parent rocks consist of subangular to subrounded quartz grains (0.2 to 0.5 mm across) forming a self-supporting framework with occasional silica overgrowths. The middle horizon is dominated by pseudobreccia fabric consisting of black iron rich "clasts" encased by yellow to pale brown "matrix" of silicified sandstone or vice-versa. The iron rich "clasts" consist mainly of massive earthy goethite and clay together with discrete skeletal quartz grains. Such grains are often corroded, embayed and completely coated by massive or colloform goethite. The surrounding "matrix" is formed of tightly interlocked quartz grains with or without goethite coatings. Lenticular bodies and irregular pockets of iron-rich pisolites are commonly distributed within this horizon (P1. IVe). The pisolites are spherical and ellipsoidal in shape, ranging in diameter from 0.2 to 0.7 cm and consist of concentric laminae of goethite and kaolinite without obvious nuclei. They show signs of *in situ* brecciation and usually cemented by equigranular mosaic quartz and / or calcite (P1. IVf, g). The uppermost hard cap of this ferricrete profile is formed of concretionary aggregated iron rich crusts together with ferruginated plant molds, algal filaments and skeletal quartz grains of coarse-sand to pebble size. Calcite, barite and gypsum, arranged according to their order of crystallization, represent primary void filling.

Ferricrete overlying the karstified carbonates of the Naqb Formation

The best example of this ferricrete type is that of G. Ghorabi, where it attains up to 13 m thick and consists of an upper indurated horizon overlying highly subdued and altered Eocene carbonates mixed with iron ore deposits (El Aref and Lotfy, 1989). Ferricrete duricrust, up to 3 m thick, is also widespread all over the northern scarp of the depression, forming the upper cliff segment of the slope profile. The ferricrete top is smooth and comparatively even. It is interrupted in places by smallish barren spots, where prominences of karstified dolostones with no ferricrete cover pierce the ferricrete deposits. Representative ferricrete profile, measured at Naqb El Harra, is illustrated in Figure 7. The parental dolostones

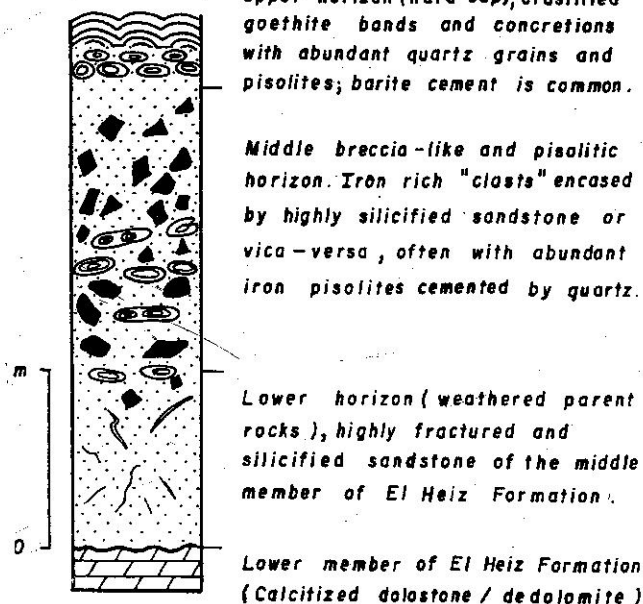
El Aref, El Dougdoug, and Mesaed,

Fig. 6. Ferricrete profile overlying the middle sandstone member of El Heiz Formation (section 12', Fig. 1).

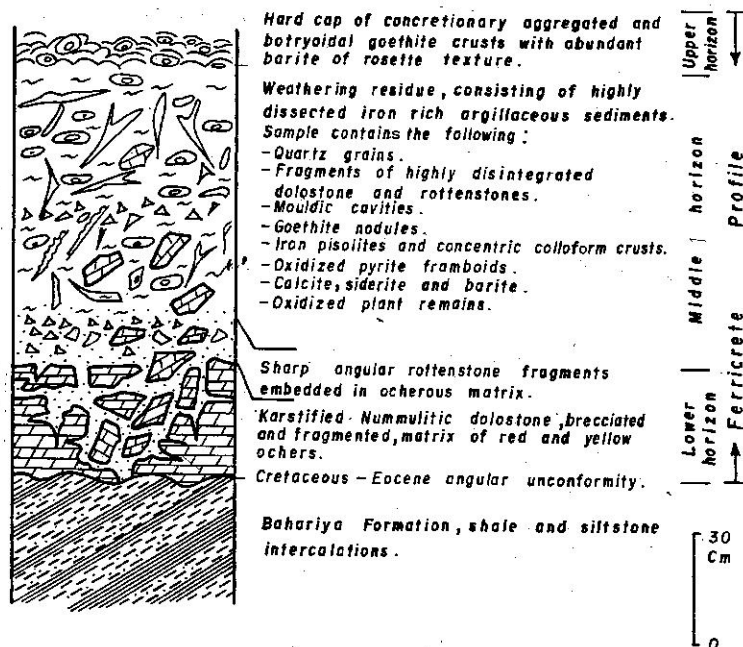


Fig. 7. Ferricrete profile overlying the karstified dolostones of the Naqb Formation, Naqb El Harra (section 2', Fig. 1).

(consisting mainly of ferroan dolomite) are highly affected by dedolomitization that resulted in the formation of calcitized dolostone, dedolomite, ferruginated dedolomite and rottenstone varieties, through progressive dissolution, replacement of the ferroan dolomite by calcite and concentration of iron sesquioxides. Advanced brecciation leaves residual fragments, 5 to 20 cm in diameter, riddled with holes (P1. IVh). The brecciated dedolomitized and ferruginated varieties grade upward into sharp angular rottenstone clasts embedded in ocherous matrix. The middle horizon of this profile contains higher proportion of iron rich argillaceous sediments having a gradational contact with the karstified dolostones below. It includes highly calcitized dolostone and rottenstone fragments and skeletal quartz grains, engulfed by the ferruginous matrix. The matrix is formed of earthy goethite and clay and includes dissected goethite glaeboles (Pl. IVi), oxidized pyrite framboids and abundant vugs partially filled with oxidized spindle-shape siderite crystals and calcite (P1. IVj, k). Diffused goethite streaks and goethite pisolites appear at different places in the matrix. Micronodules of goethite grow frequently, within these streaks. Mouldic cavities, filled with geopetal pyrite framboids, are locally abundant in the matrix. The intergranular spaces within these cavities are usually occupied by siderite, blocky calcite, barite, gypsum and anhydrite. The upper hard cap of this profile, up to 20 cm thick, is composed almost entirely of dark brown to black concretionary aggregated colloform crusts of goethite, hematite and less abundant Mn hydroxide. Root molds, oxidized algal filaments and plant tissues are also recorded. Framboidal pyrite, colloform goethite, ochers and chalcedony are the main components of the preserved plant remains. Barite crystals fill spaces within the botryoidal goethite crusts and tend to form rosettes, sometimes encrusted by younger goethite layers.

DISCUSSION AND CONCLUSIONS

The studied ferricrete profile is made up of three successive horizons: a) the fresh parent rocks at the bottom grading upward into brecciated, mottled, silicified and ferruginated weathered rocks; b) a middle breccia (illuvial) horizon, and c) an upper sandy hard cap rich in organic remains, pyrite framboids and crustified goethite. Each horizon gradually penetrates into the next underlying layer. These horizons are dominated by the following megascopic and microscopic fabrics, which are characteristic of any laterite deposits: pisolites, glaeboles, spherulites, concretions, crustification, coatings or films, cockade, cavity and vug fillings; cellular structures and preserved plant remains. The main diagenetic processes involved during the formation of the ferricrete duricrust capping the Cenomanian clastics are: diffusion, dissolution, concentration of iron sesquioxides and

kaolinitic clays, silicification and ferruginization, obliteration of the original grain-supported fabric and creation of new fabrics (floating and matrix fabrics), development of pisolites, glaebules, concretions and encrustations and authigenic growth of pyrite framboids, barite, calcite and evaporitic minerals. Dissolution, brecciation, formation of mouldic cavities, dedolomitization, concentration of iron sesquioxides, formation of rottenstone and late cementation by quartz, barite and calcite are the main diagenetic processes involved during the formation of the ferricrete overlying the karstified Eocene carbonates.

In discussing the origin of the studied ferricrete and the soil environments involved during its formation, several factors should be considered: paleoclimatic conditions, paleotopography, paleohydrological factors (water activity), the role of plant cover and microorganisms (biogenic factors), geochemical and physico-chemical factors, colloidal chemical factors, composition and physical characters of the rocks exposed to lateritization and time factors.

The present high-lying ferricrete caps represent remnants of former extensive lateritized plain that demarcates the senile stage of an old erosion cycle. During the rainy seasons, leaching and drainage predominate, above the water table. The groundwater level subsides during the dry season, following the rainy season and the weathering zone is dried out and processes of oxidation and lithification prevail. According to Roquin et al. (1990), in a sequence of successive horizons of ferricrete profile differing in Fe contents, the highest one is the richest in Fe and is also the oldest and most evolved ferricrete facies, whereas the mottled zone is the poorest in Fe and is the youngest and least evolved zone. The downward movement of the different laterite horizons, i.e. continuous conversion of C horizon to B and B to A, induces a general and vertical descent of the landscape surfaces, as a function of time and downward migration of the water table. Accordingly, the iron of the studied ferricrete is suggested to be derived from above, through *in situ* lateritization of the exposed iron bearing Cretaceous and Eocene rocks (ferruginous sandstones, shales, ironstones and dolomites) and continuous lowering of the relief and vadose zone with time. Oxidation of the heavy minerals (ilmenite and magnetite) is another source of iron. An important requirement of intense leaching is that the parent rocks should be percolated by surface water in order to promote chemical alteration by hydrolysis and to remove in solution the alteration products (silica, alkalis, alkali earth ... etc.). This condition is satisfied by the permeable (fractured) Cretaceous clastics and the soluble Eocene carbonates. Since sesquioxides become more resistant to erosion, subsequent erosional processes elevate the ferricrete profile to form plateaux, ridges and hill tops.

The components of the studied ferricrete profile provide an important reflection of the chemical and biogenic processes that governed the soil formation (ferricrete formation). The concentration and distribution of Fe, Si, Al, Ca and Ba bearing minerals throughout the ferricrete horizons can be attributed to the mobility and geochemical behaviour of these elements during the course of weathering. On the other hand, the abundant distribution of plant remains and pyrite framboids in the A horizon suggests that the weathering processes have been prevailed under vegetation cover. Accumulation and decay of vegetal debris lower the oxidation-reduction potential in the ground and introduce strong organic acids which give rise to an acidic pH and are liable to complex the metallic cations and to carry them toward deeper layers (Saxby, 1976). During the initial stages of lateritization, the reducing and acidic environments lead to the mobilization of iron as Fe^{2+} or organic complexes far from the site of release, then gradually accumulates in the illuvial (B) horizon. Under oxidized and alkaline conditions the iron precipitates as Fe^{3+} (Norton, 1973). The ochreous materials reveal direct deposition from suspension, whereas colloform concretions and encrustations indicate segregation from colloidal suspensions that appear to be delivered simultaneously with the earthy products, coagulated and settled separately as a function of their specific gravity or the pH of the environment. Isolated goethite pisolites, glaebules and concretions indicate nucleated growth of cryptocrystalline goethite in discrete zone within the host earthy matrix. Goethite also tends to occur as amorphous coatings, gradually transforming to crystalline forms (goethite and hematite) as the amounts present increase.

Tardy and Nahon (1985) and Nahon (1987) revealed that the distribution of goethite and hematite in soil is regulated by water activity : a solution that becomes saturated with respect to iron minerals should precipitate goethite in water of high activity and hematite in water of low activity. As the activity of water is related to sizes of pores (Bourrie and Pedro, 1979), hematite stability field is extending as the porosity and related water decrease (Tardy and Nahon, 1985). This is expressed by the formation of hematite in the residual vugs and cavities distributed within the earthy matrix or left behind the younger goethite crusts. Al being relatively leached in the superficial acid zone and well aerated layers of the laterite profile (at $\text{pH} > 4$ and $\text{Eh} > 0.4$, Norton, 1973), before being redeposited in deeper layers and is moving further than Fe^{3+} (Duchaufour, 1968 and Lelong et al., 1976). This can explain the concentration of concretionary aggregated and botryoidal goethite crusts in the upper A horizon and the accumulation of kaolinitic clays in the B horizon. Under tropical but less intensively leached condition, solutions are not so highly diluted and silica is not released so easily, a part of it combines with Al to give kaolinite and the Fe continuous to assume hydroxide or oxide forms (Lelong et

al., 1976). The formation of kaolinite leads to continuous consuming of aluminum from solution and gradual increasing of the solubility of silica (Jones and Handreck, 1963). The present microscopic observations revealed that the continuous accumulation of iron sesquioxides and clay was accompanied by gradual corrosion of the original skeletal quartz grains and quartz overgrowths, reflecting alkaline condition. The silica solubility increases with pH, from nearly insoluble in strongly acidic cool environment through slightly soluble in humid conditions of pH 6 to 8 and becomes soluble in alkaline system of pH above 8 (Norton, 1973). Lovering (1959) and Bardossy (1982) recorded very rapid desilication under the chemical action of a living plant cover.

In addition to the pH and Eh, water temperature is another important factor for lateritization and desilication. According to Okamoto et al. (1957) and Krauskopf (1976), the solubility of amorphous silica gel and the rate of silica dissolution increase more than threefold in the temperatures range from 0 to 58 °C. The studied ferricrete profiles are characterized by the presence of a silicified zone within the lower parts of the B horizons, similar to that detected by Mohr (1933) and Mountain (1951) within the lower parts of the ferricrete profiles of the equatorial regions. Such silicified zone indicates downward migration of silica bearing solution under leaching climates, while Fe and Al are not very mobile and accumulated relatively in the upper horizon. The corrosion of quartz grains, the formation of silicified zones within the ferricrete profiles as well as redeposition of silica as quartz overgrowths or late cement within crustified goethite layers or between goethite pisolites reflect seasonal changes in the pH and Eh conditions which in turn reflect seasonal fluctuation of the water table. The formation of later blocky calcite cement and nodules, rosette barite crystals, barite stalactites and evaporitic minerals, especially in the A horizons, suggests final successive crystallization differentiation of the most mobile elements through evapotranspiration processes during dewatering in arid to semiarid climate.

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